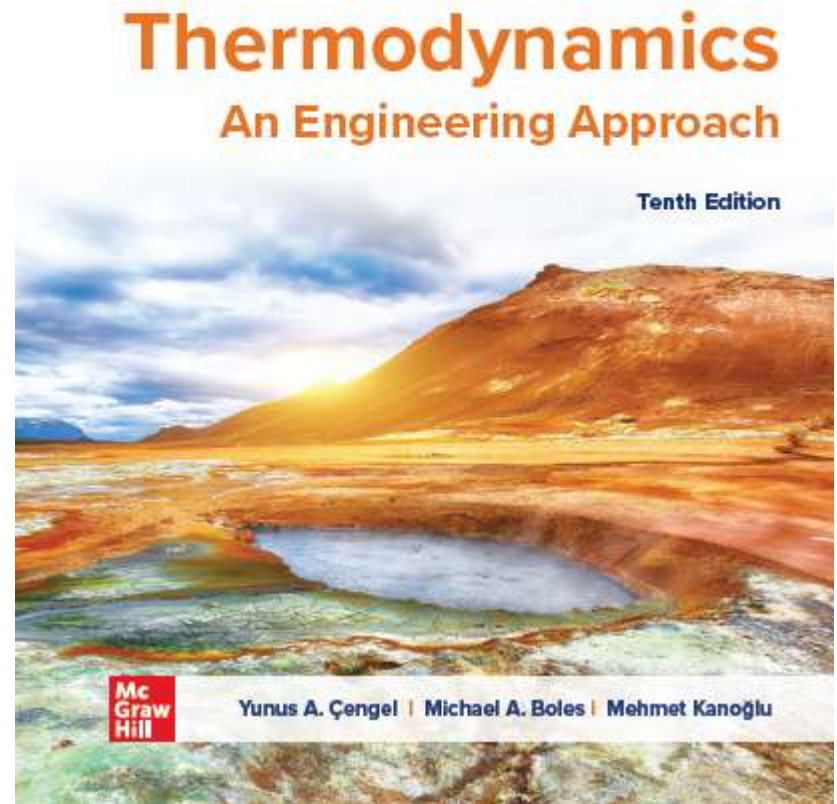


Chapter 4

Energy Analysis of Closed Systems

Thermodynamics: An Engineering
Approach, 10th Edition
Yunus A. Cengel | Michael A. Boles |
Mehmet Kanoglu McGraw-Hill, 2024



Objectives

- Examine the moving boundary work or $P dV$ work commonly encountered in reciprocating devices such as automotive engines and compressors.
- Identify the first law of thermodynamics as simply a statement of the conservation of energy principle for closed (fixed mass) systems.
- Develop the general energy balance applied to closed systems.
- Define the specific heat at constant volume and the specific heat at constant pressure.
- Relate the specific heats to the calculation of the changes in internal energy and enthalpy of ideal gases.
- Describe incompressible substances and determine the changes in their internal energy and enthalpy.
- Solve energy balance problems for closed (fixed mass) systems that involve heat and work interactions for general pure substances, ideal gases, and incompressible substances.

4–1 Moving Boundary Work ¹

Moving boundary work ($P dV$ work):

The expansion and compression work in a piston-cylinder device.

$$\delta W_b = F ds = P A ds = P dV$$

$$W_b = \int_1^2 P dV \quad (\text{kJ})$$

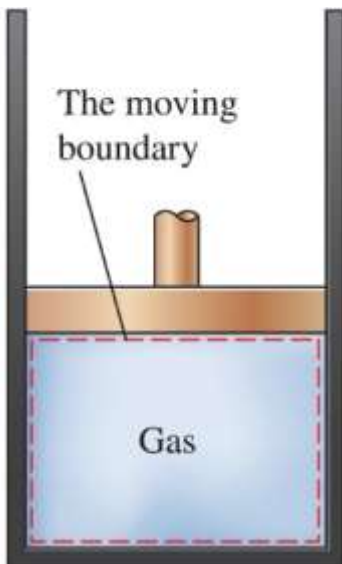


Figure 4–1

The work associated with a moving boundary is called boundary work.

Quasi-equilibrium process: A process during which the system remains nearly in equilibrium at all times.

W_b is positive $\rightarrow$ for expansion

W_b is negative $\rightarrow$ for compression

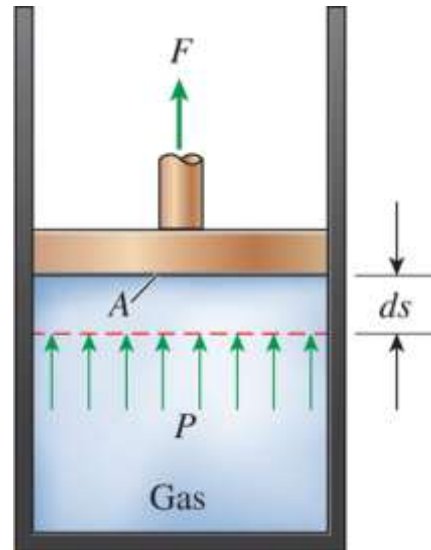


Figure 4–2

A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount ds .

[Access the text alternative for slide images.](#)

4–1 Moving Boundary Work ₂

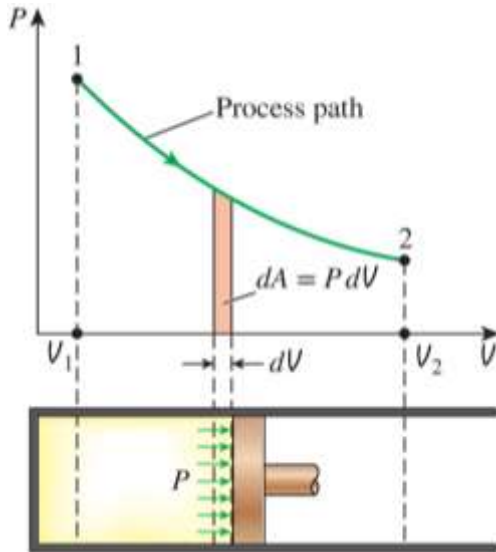


Figure 4–3

The area under the process curve on a P - V diagram represents the boundary work.

$$\text{Area} = A = \int_1^2 dA = \int_1^2 p \, dV$$

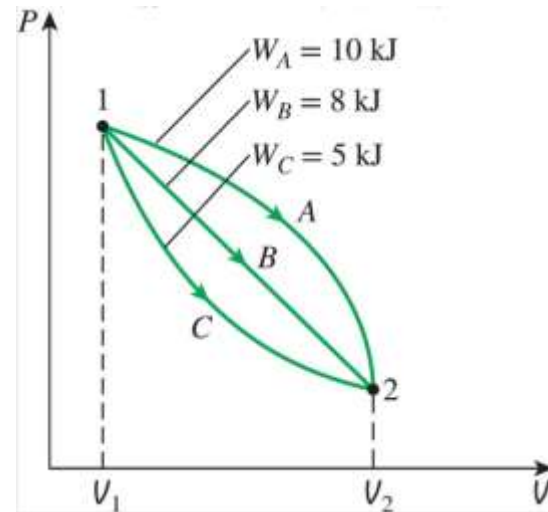


Figure 4–4

The boundary work done during a process depends on the path followed as well as the end states.

The area under the process curve on a P - V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.

[Access the text alternative for slide images.](#)

4–1 Moving Boundary Work ₃

Generalized boundary work relation

$$W_b = \int_1^2 P_i dV$$

P_i is the pressure at the inner face of the piston.

In a car engine, the boundary work done by the expanding hot gases is used to overcome friction between the piston and the cylinder, to push atmospheric air out of the way, and to rotate the crankshaft.

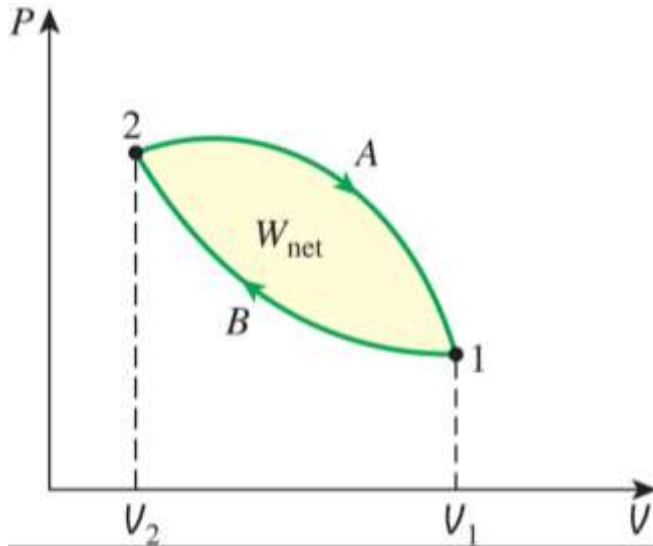


Figure 4–5

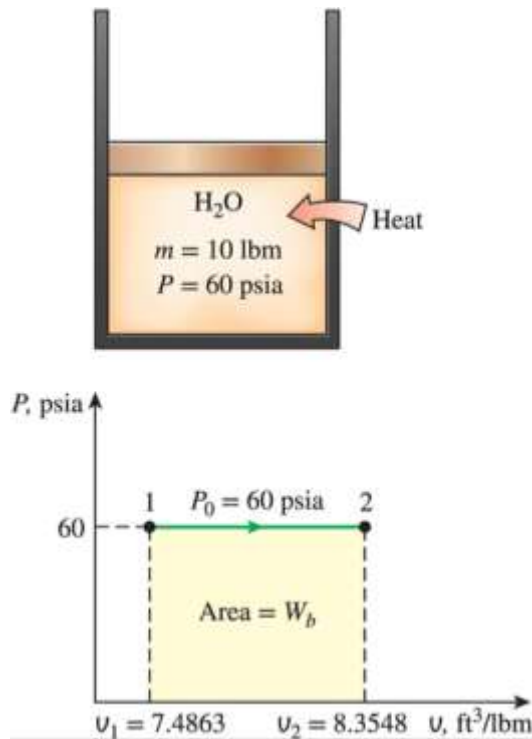
The net work done during a cycle is the difference between the work done by the system and the work done on the system.

$$W_b = W_{\text{friction}} + W_{\text{atm}} + W_{\text{crank}} = \int_1^2 (F_{\text{friction}} + P_{\text{atm}} A + F_{\text{crank}}) dx$$

[Access the text alternative for slide images.](#)

4–1 Moving Boundary Work ⁴

Boundary Work for a Constant-Pressure Process



$$W_b = \int_1^2 P_i dV$$

$$= P_0 \int_1^2 dV$$

$$= P_0 (V_2 - V_1)$$

$$= mP_0 (v_2 - v_1)$$

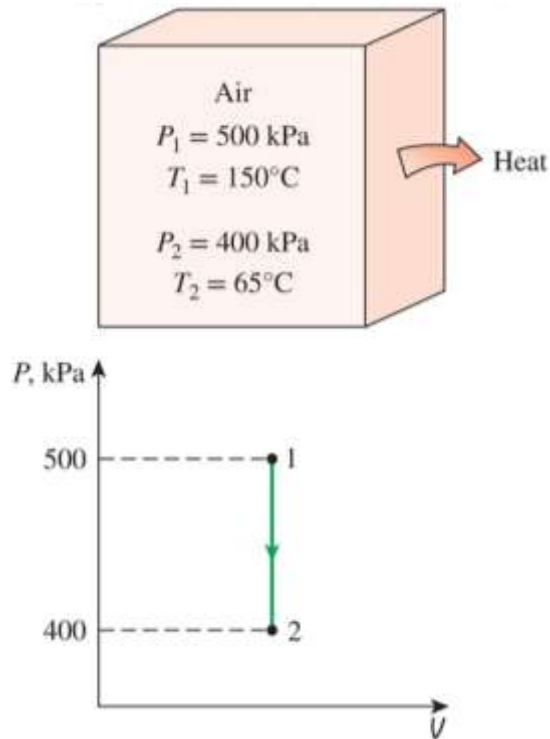
Figure 4–7

Schematic and P - v diagram for Example 4–2.

[Access the text alternative for slide images.](#)

4–1 Moving Boundary Work ⁵

Boundary Work for a Constant-Volume Process



$$W_b = \int_1^2 P dV = 0$$

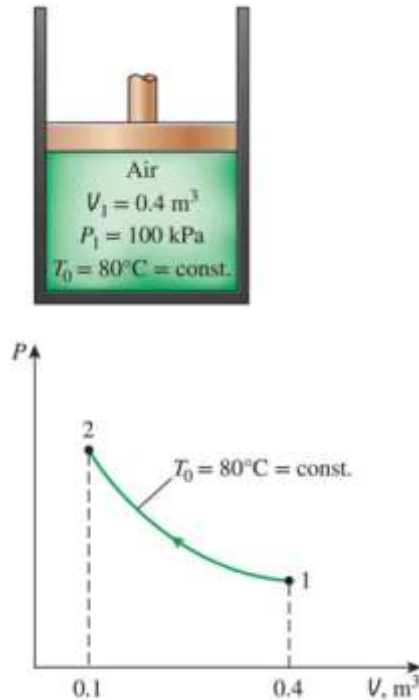
Figure 4–6

Schematic and P - V diagram for Example 4–1.

[Access the text alternative for slide images.](#)

4–1 Moving Boundary Work ⁶

Boundary Work for an Isothermal Compression Process



$$W_b = \int_1^2 P dV = \int_1^2 C V^{-1} dV = P V \ln \left(\frac{V_2}{V_1} \right)$$

$$P V = m R T_0 = C \quad \text{or} \quad P = \frac{C}{V} \quad C \text{ is a constant}$$

$$W_b = \int_1^2 P dV = \int_1^2 \frac{C}{V} dV = C \int_1^2 \frac{dV}{V}$$

$$= C \ln \left(\frac{V_2}{V_1} \right) = P_1 V_1 \ln \left(\frac{V_2}{V_1} \right)$$

Figure 4–8

Schematic and P - V diagram for Example 4–3.

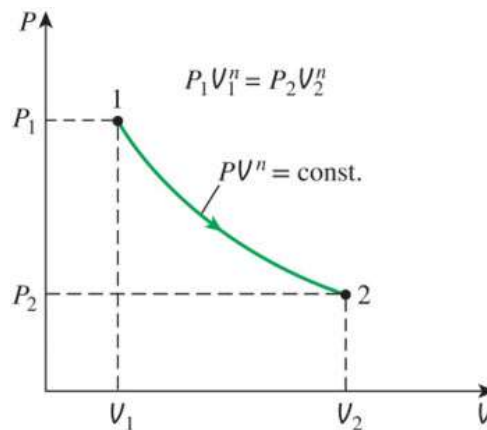
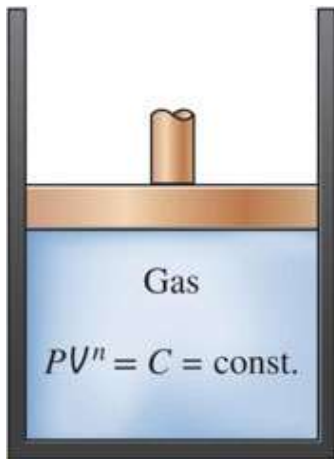
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4–1 Moving Boundary Work ₇

Boundary Work for a Polytropic Process

$$PV^n = C \quad P = CV^{-n} = C$$

$$W_b = \int_1^2 P dV = \int_1^2 CV^{-n} dV = C \frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2 V_2 - P_1 V_1}{1-n}$$



$$W_b = \frac{mR(T_2 - T_1)}{1-n} \quad n \neq 1 \text{ (kJ)} \quad \text{For ideal gas}$$

Figure 4–9

Schematic and P - V diagram for a polytropic process.

[Access the text alternative for slide images.](#)

4-2 Energy Balance for Closed Systems ¹

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, Kinetic, Potential, etc., energies}} \quad \text{kJ}$$

Energy balance for any system undergoing any process

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}} / dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad \text{kW}$$

Energy balance in the rate form

The total quantities are related to the quantities per unit time

$$Q = \dot{Q} \Delta t \quad W = \dot{W} \Delta t \quad \Delta E = \left(\frac{dE}{dt} \right) \Delta t \quad \text{kJ}$$

$$e_{\text{in}} - e_{\text{out}} = \Delta e_{\text{system}} \quad (\text{kJ/kg})$$

Energy balance per unit mass basis

$$\delta E_{\text{in}} - \delta E_{\text{out}} = dE_{\text{system}} \quad \text{or} \quad \delta e_{\text{in}} - \delta e_{\text{out}} = de_{\text{system}}$$

Energy balance in differential form

$$W_{\text{net,out}} = Q_{\text{net,in}} \quad \text{or} \quad \dot{W}_{\text{net,out}} = \dot{Q}_{\text{net,in}}$$

Energy balance for a cycle

4-2 Energy Balance for Closed Systems ²

$$W_{\text{net,out}} = Q_{\text{net,in}} \quad \text{or} \quad \dot{W}_{\text{net,out}} = \dot{Q}_{\text{net,in}} \quad (\text{for a cycle})$$

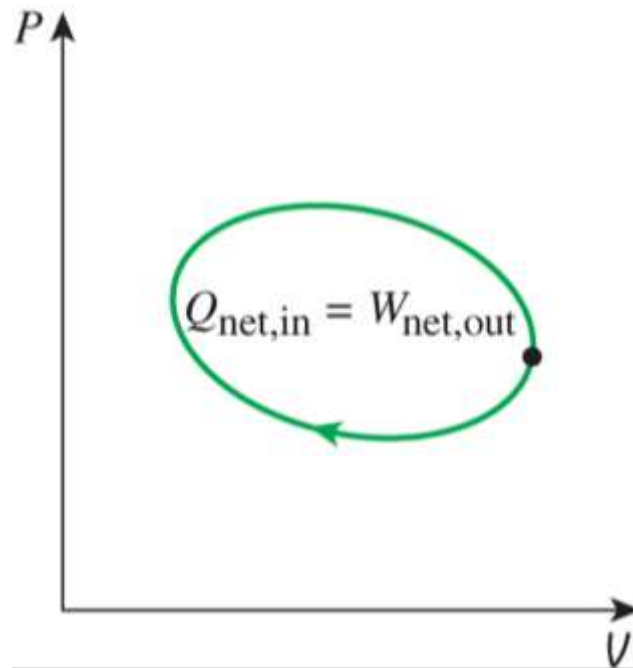


Figure 4-11

For a cycle $\Delta E = 0$, thus net heat input is equal to net work output.

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4-2 Energy Balance for Closed Systems ³

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$$

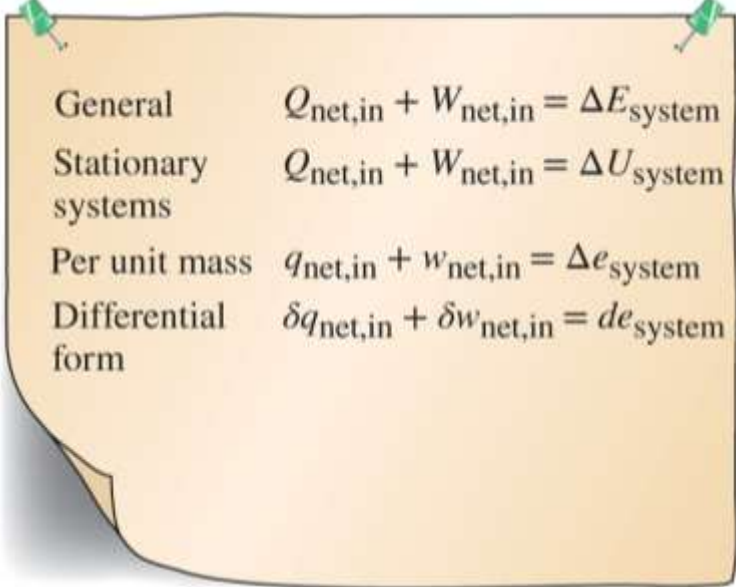
$$(Q_{\text{in}} + W_{\text{in}}) - (Q_{\text{out}} + W_{\text{out}}) = \Delta U + \Delta KE + \Delta PE$$

$$Q_{\text{net,in}} + W_{\text{net,in}} = \Delta U + \Delta KE + \Delta PE$$

$$Q_{\text{net,in}} = Q_{\text{in}} - Q_{\text{out}}$$

$$W_{\text{net,in}} = W_{\text{in}} - W_{\text{out}}$$

The first law cannot be proven mathematically, but no process in nature is known to have violated the first law, and this should be taken as sufficient proof.



General	$Q_{\text{net,in}} + W_{\text{net,in}} = \Delta E_{\text{system}}$
Stationary systems	$Q_{\text{net,in}} + W_{\text{net,in}} = \Delta U_{\text{system}}$
Per unit mass	$q_{\text{net,in}} + w_{\text{net,in}} = \Delta e_{\text{system}}$
Differential form	$\delta q_{\text{net,in}} + \delta w_{\text{net,in}} = de_{\text{system}}$

Figure 4-12

Various forms of the first-law relation for closed systems.

4-2 Energy Balance for Closed Systems ⁴

Constant-Pressure Processes of Closed Systems

For a constant-pressure expansion or compression process:

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$$

$$\Delta U + W_b = \Delta H$$

$$(Q_{\text{in}} + W_{\text{in}}) - (Q_{\text{out}} + W_{\text{out}}) = \Delta U + \Delta KE + \Delta PE$$

$$Q_{\text{net,in}} + W_{\text{net, in}} = \Delta U + \Delta KE + \Delta PE$$

$$Q_{\text{net,in}} + W_{\text{net other, in}} - W_{\text{b,out}} = \Delta U + \Delta KE + \Delta PE$$

$$W_b = W_{\text{b,out}} = P(V_2 - V_1) = P_2 V_2 - P_1 V_1$$

$$P_0 = P_2 = P_1 \rightarrow Q_{\text{net,in}} + W_{\text{net other,in}} = (U_2 + P_2 V_2) - (U_1 + P_1 V_1) + \Delta KE + \Delta PE$$

$$H = U + PV$$

$$(U_2 + P_2 V_2) - (U_1 + P_1 V_1) = H_2 - H_1$$

$$Q_{\text{net,in}} + W_{\text{net other,in}} = \Delta H + \Delta KE + \Delta PE$$

4-2 Energy Balance for Closed Systems ⁵

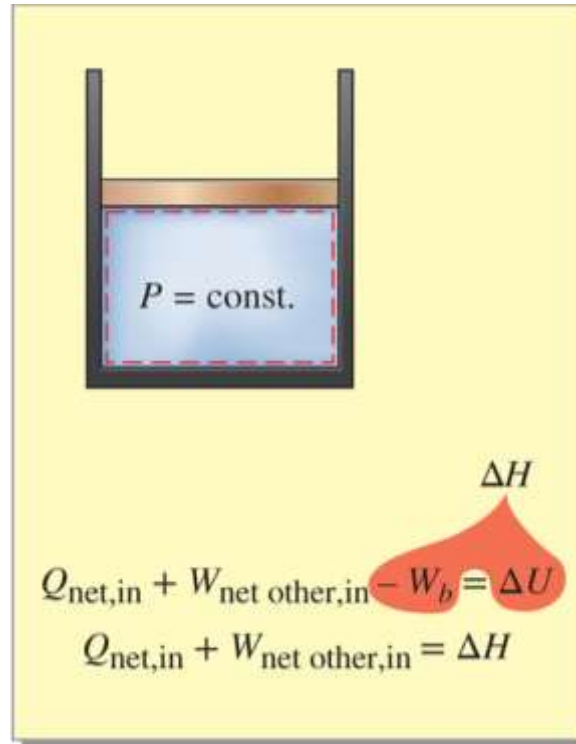


Figure 4-13

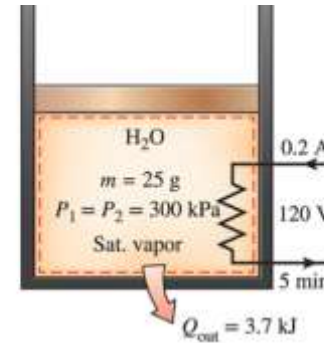
For a closed system undergoing a quasi-equilibrium, $P = \text{constant}$ process, $\Delta U + W_b = \Delta H$.

Note that this relation is NOT valid for closed systems processes during which pressure DOES NOT remain constant.

[Access the text alternative for slide images.](#)

4–2 Energy Balance for Closed Systems ⁶

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, Potential, etc., energies}}$$



$$W_{\text{e,in}} - Q_{\text{out}} - W_b = \Delta U$$

$$W_{\text{e,in}} - Q_{\text{out}} = \Delta H = m(h_2 - h_1)$$

since $P = \text{constant}$

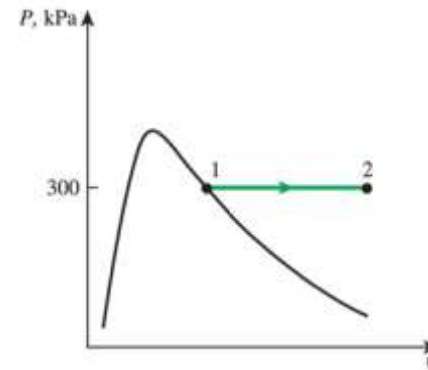


Figure 4–14

Schematic and P - v diagram for Example 4–5.

[Access the text alternative for slide images.](#)

4-2 Energy Balance for Closed Systems ⁷

Unrestrained Expansion of Water

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, Potential, etc., energies}}$$

$$Q_{\text{out}} = \Delta U = m(u_2 - u_1)$$

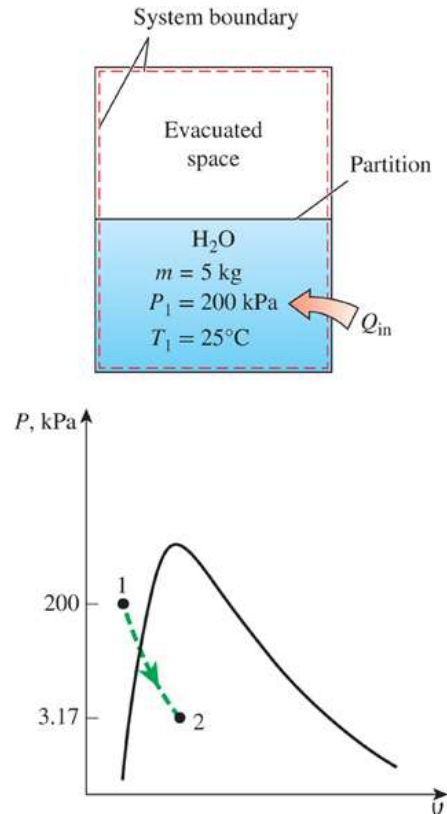


Figure 4-15
Schematic and P - v diagram for
Example 4-6.

[Access the text alternative for slide images.](#)

4–3 Specific Heats ¹

Specific heat at constant volume, c_v : The energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

Specific heat at constant pressure, c_p : The energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.

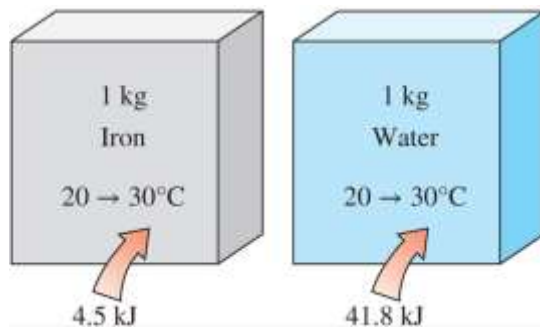


Figure 4–17

It takes different amounts of energy to raise the temperature of different substances by the same amount.

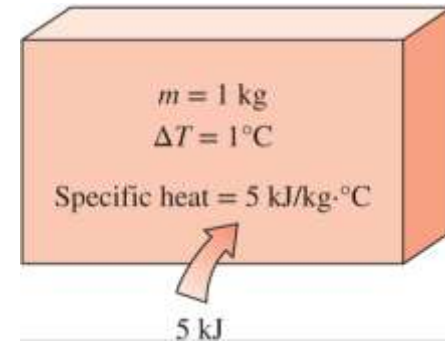


Figure 4–18

Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

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4–3 Specific Heats ²

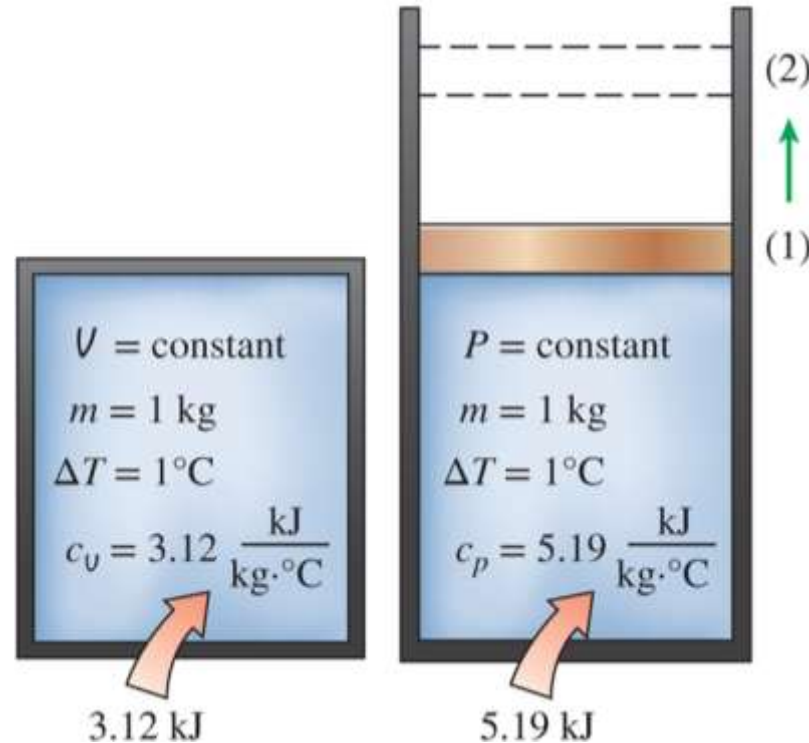


Figure 4–19

Constant-volume and constant-pressure specific heats c_v and c_p
(values given are for helium gas).

[Access the text alternative for slide images.](#)

4–3 Specific Heats ³

Consider a fixed mass in a stationary closed system undergoing a constant-volume process

$$\delta e_{\text{in}} - \delta e_{\text{out}} = du$$

$$c_v dT = du \quad \text{at constant value}$$

$$c_v = \left(\frac{\partial u}{\partial T} \right)_v$$

Consider a constant-pressure expansion or compression process

$$c_p = \left(\frac{\partial h}{\partial T} \right)_p$$

The equations are valid for *any* substance undergoing *any* process.

c_v is related to the changes in *internal energy* and c_p to the changes in *enthalpy*.

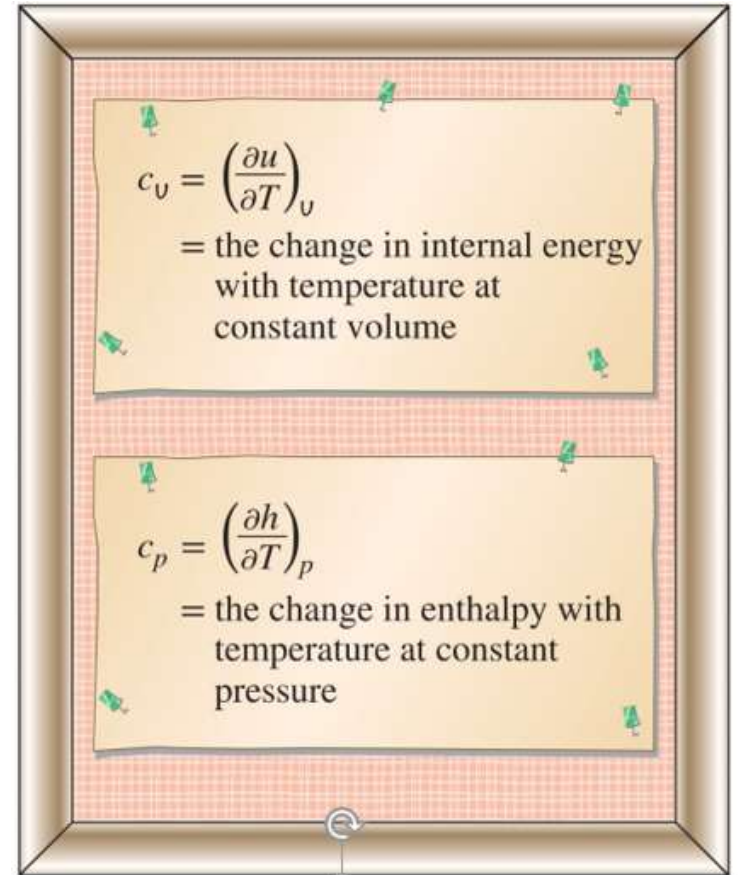


Figure 4–20

Formal definitions of c_v and c_p

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4–3 Specific Heats ⁴

c_v and c_p are properties.

The specific heats of a substance depend on the state.

The energy required to raise the temperature of a substance by one degree is different at different temperatures and pressures.

A common unit for specific heats is $\text{kJ/kg}\cdot^\circ\text{C}$ or $\text{kJ/kg}\cdot\text{K}$.

Are these units identical?

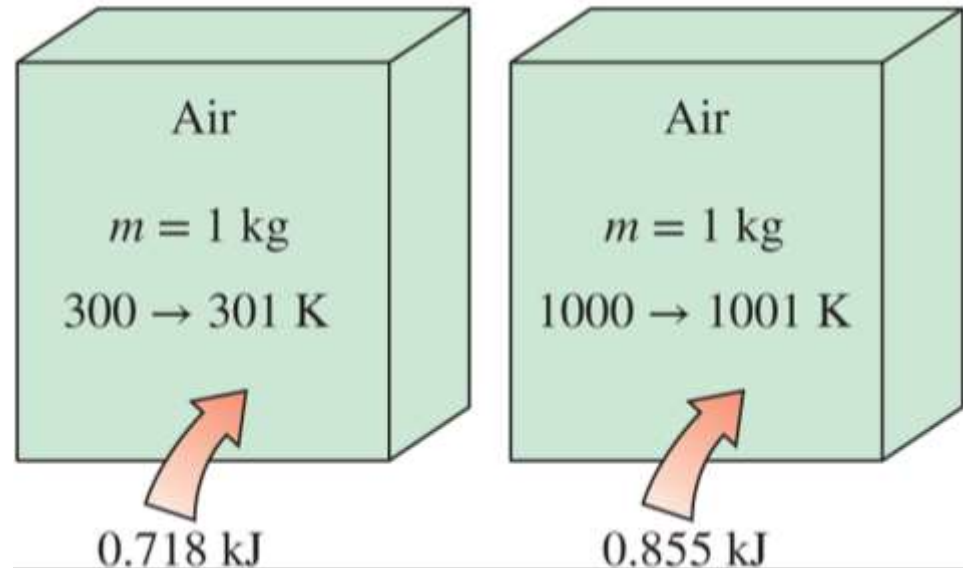


Figure 4–21

The specific heat of a substance changes with temperature.

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ¹

Joule showed using this experimental apparatus that $u = u(T)$.

$$\left. \begin{array}{l} h = u + Pv \\ Pv = RT \end{array} \right\} h = u + RT$$

$$u = u(T); h = h(T)$$

$$du = c_v(T)dT$$

$$dh = c_p(T)dT$$

Internal energy and enthalpy change of an ideal gas

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)dT \quad (\text{kJ/kg})$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)dT \quad (\text{kJ / kg})$$

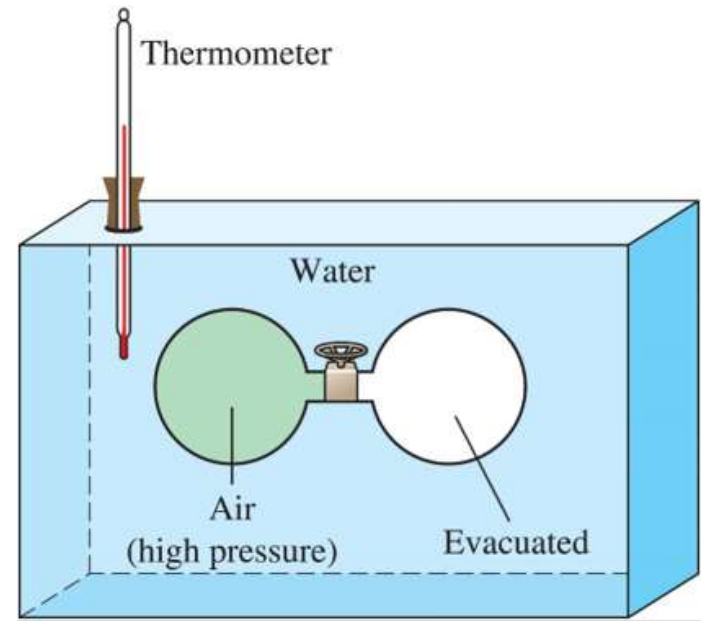


Figure 4–22

Schematic of the experimental apparatus used by Joule.

[Access the text alternative for slide images.](#)

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ²

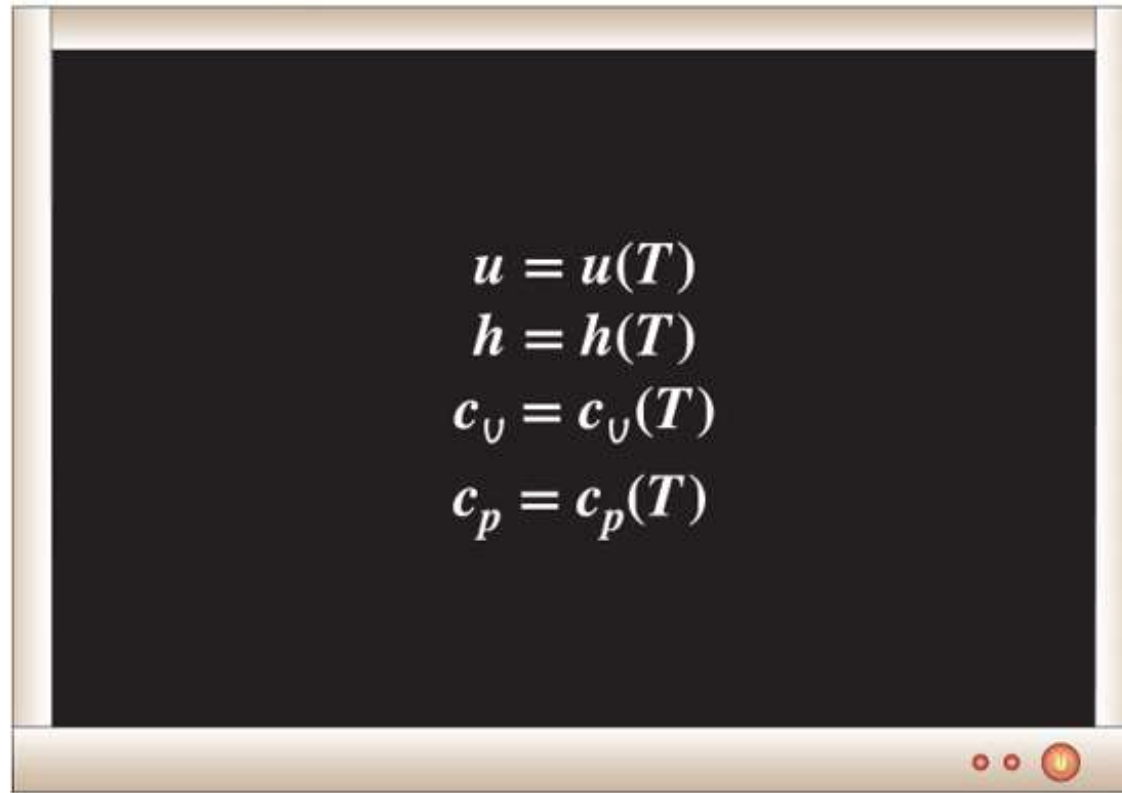

$$\begin{aligned}u &= u(T) \\h &= h(T) \\c_v &= c_v(T) \\c_p &= c_p(T)\end{aligned}$$

Figure 4–23

For ideal gases, u, h, c_v and c_p vary with temperature only.

[Access the text alternative for slide images.](#)

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ³

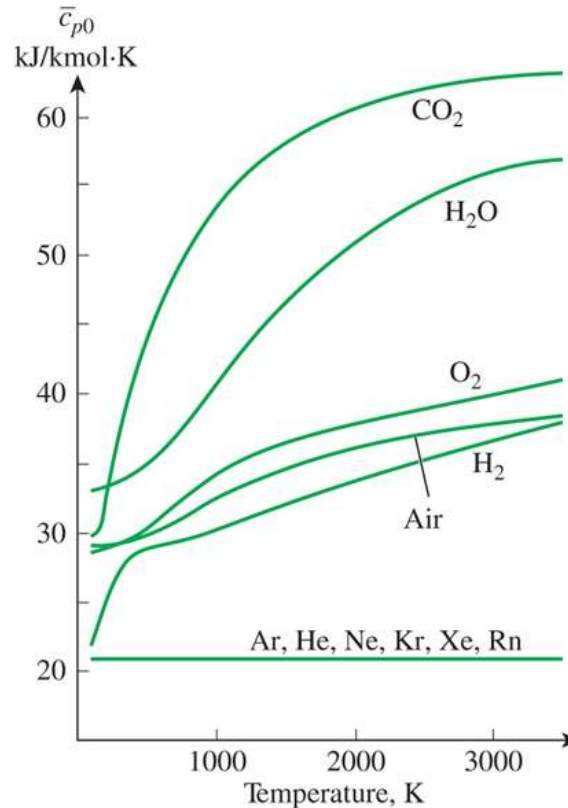


Figure 4–24

Ideal-gas constant-pressure specific heats for some gases (see Table A–2c for c_p equations).

[Access the text alternative for slide images.](#)

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ⁵

Internal energy and enthalpy change when specific heat is taken constant at an average value

$$u_2 - u_1 = c_{v,\text{avg}}(T_2 - T_1) \quad (\text{kJ/kg})$$

$$h_2 - h_1 = c_{p,\text{avg}}(T_2 - T_1) \quad (\text{kJ/kg})$$

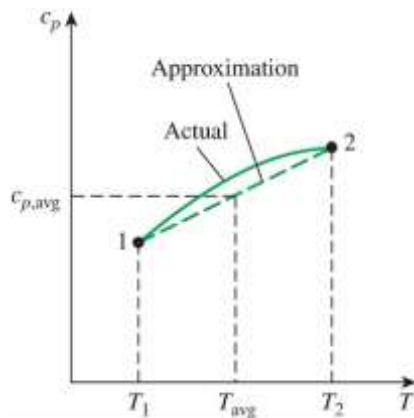


Figure 4–26

For small temperature intervals, the specific heats may be assumed to vary linearly with temperature.

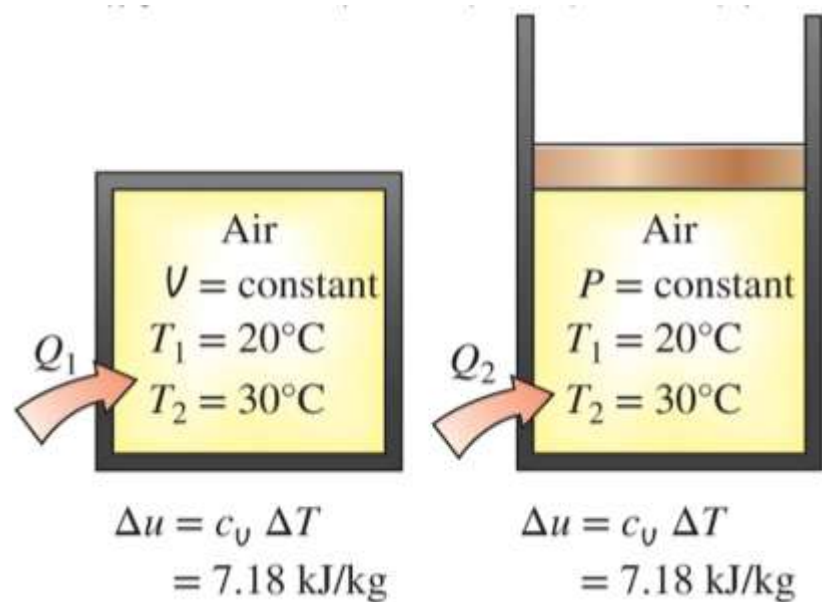


Figure 4–27

The relation $\Delta U = c_v \Delta T$ is valid for any kind of process, constant-volume or not.

[Access the text alternative for slide images.](#)

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ⁶

Three ways of calculating Δu and Δh

1. By using the tabulated u and h data.
This is the easiest and **most accurate** way when tables are readily available.
2. By using the c_v or c_p relations (Table A-2c) as a function of temperature and performing the integrations. This is very inconvenient for hand calculations but quite desirable for computerized calculations. The results obtained are **very accurate**.
3. By using average specific heats. This is very simple and certainly very convenient when property tables are not available. The results obtained are **reasonably accurate** if the temperature interval is not very large.

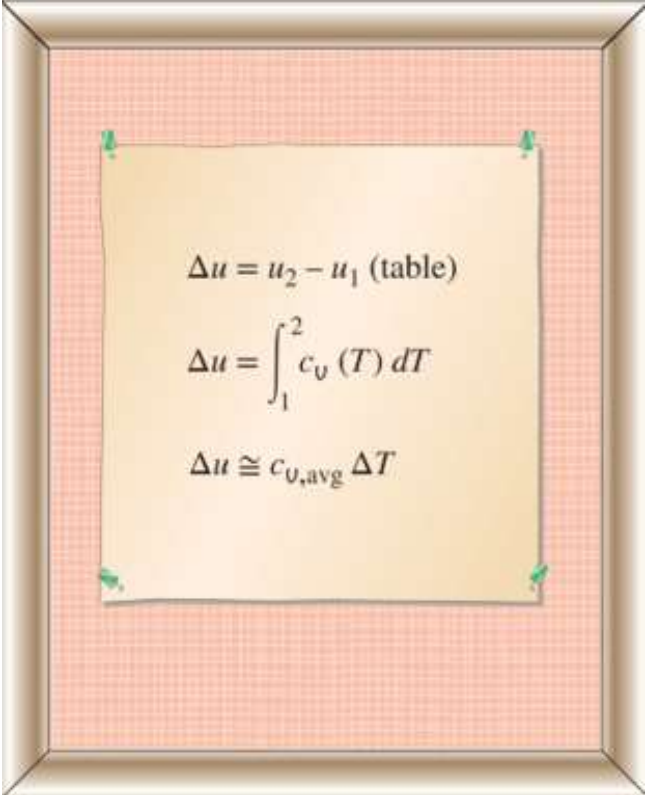

$$\Delta u = u_2 - u_1 \text{ (table)}$$
$$\Delta u = \int_1^2 c_v(T) dT$$
$$\Delta u \cong c_{v,\text{avg}} \Delta T$$

Figure 4–28

Three ways of calculating Δu .

[Access the text alternative for slide images.](#)

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ⁷

$$h = u + RT$$

$$dh = du + RdT$$

$$dh = c_p dT \text{ and } du = c_v dT$$



The relationship between c_p , c_v and R

$$c_p = c_v + R \quad (\text{kJ/kg} \cdot \text{K})$$

On a molar basis:

$$\bar{c}_p = \bar{c}_v + R_u \quad (\text{kJ/kmol} \cdot \text{K})$$

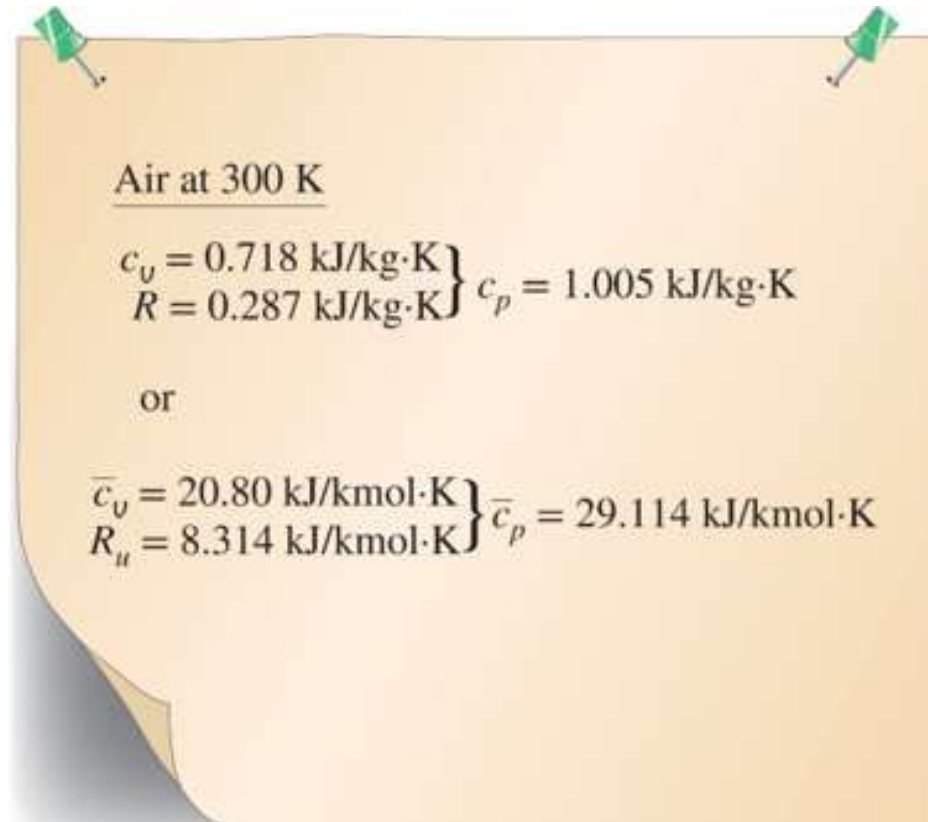
$$k = \frac{c_p}{c_v} \text{ Specific heat ratio}$$

The specific ratio varies with temperature, but this variation is mild.

For monatomic gases (helium, argon, etc.), its value is essentially constant at 1.667.

Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ₈



Air at 300 K

$$\left. \begin{array}{l} c_v = 0.718 \text{ kJ/kg}\cdot\text{K} \\ R = 0.287 \text{ kJ/kg}\cdot\text{K} \end{array} \right\} c_p = 1.005 \text{ kJ/kg}\cdot\text{K}$$

or

$$\left. \begin{array}{l} \bar{c}_v = 20.80 \text{ kJ/kmol}\cdot\text{K} \\ R_u = 8.314 \text{ kJ/kmol}\cdot\text{K} \end{array} \right\} \bar{c}_p = 29.114 \text{ kJ/kmol}\cdot\text{K}$$

Figure 4–29

The c_p of an ideal gas can be determined from a knowledge of c_v and R .

[Access the text alternative for slide images.](#)

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ⁹

Heating of a Gas in a Tank by Stirring

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$W_{\text{sh,in}} = \Delta U = m(u_2 - u_1) = mc_{v,\text{avg}}(T_2 - T_1)$$

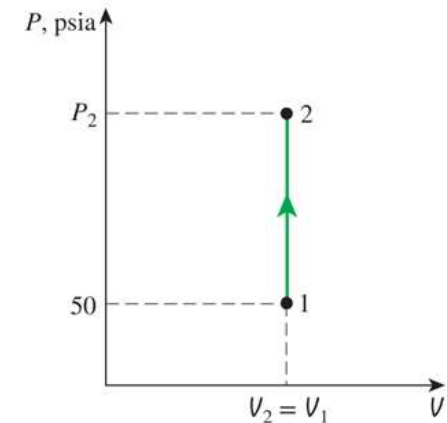
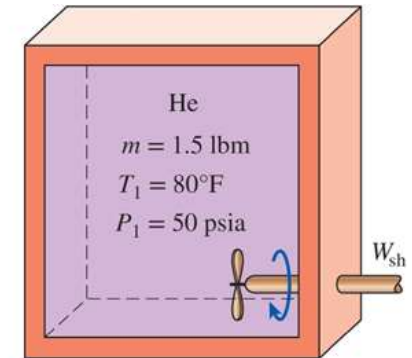


Figure 4–30

Schematic and P - V diagram for Example 4–8.

[Access the text alternative for slide images.](#)

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ¹⁰

Heating of a Gas by a Resistance Heater

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$W_{\text{e,in}} - Q_{\text{out}} - W_{\text{b,out}} = \Delta U$$

$$W_{\text{e,in}} - Q_{\text{out}} = \Delta H = m(h_2 - h_1) = mc_p(T_2 - T_1)$$

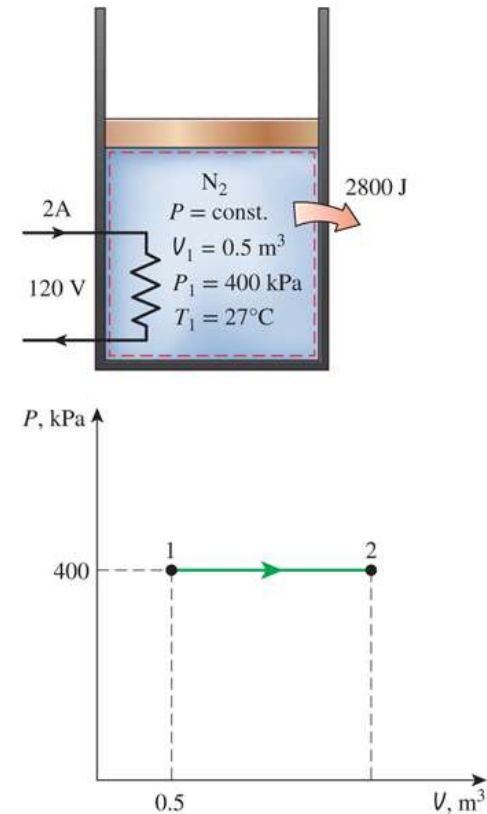


Figure 4–31

Schematic and P - V diagram for Example 4–9.

[Access the text alternative for slide images.](#)

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases ¹¹

Heating of a Gas at Constant Pressure

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$Q_{\text{in}} - W_{b,\text{out}} = \Delta U = m(u_3 - u_1)$$

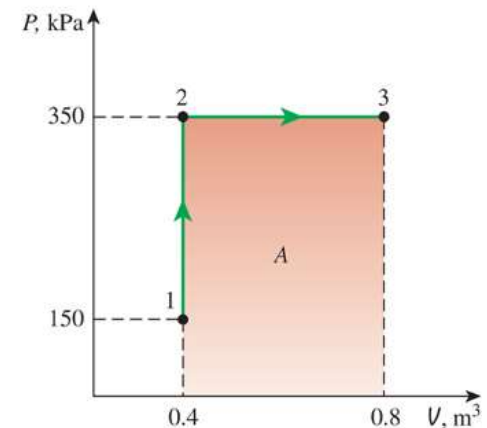
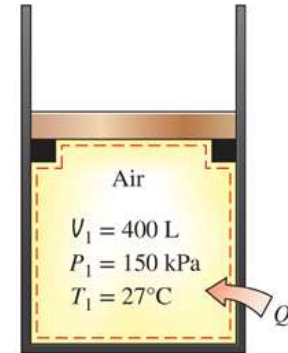


Figure 4–32

Schematic and P - V diagram for Example 4–10.

[Access the text alternative for slide images.](#)

4–5 Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids ¹

Incompressible substance: A substance whose specific volume (or density) is constant.

Solids and liquids are incompressible substances.

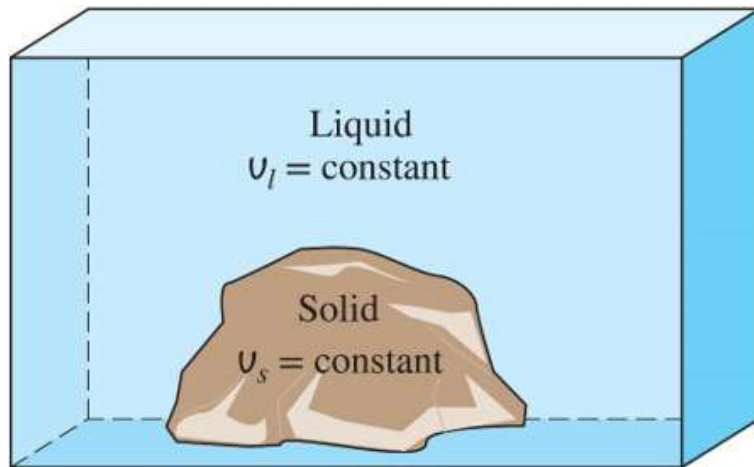


Figure 4–33

The specific volumes of incompressible substances remain constant during a process.

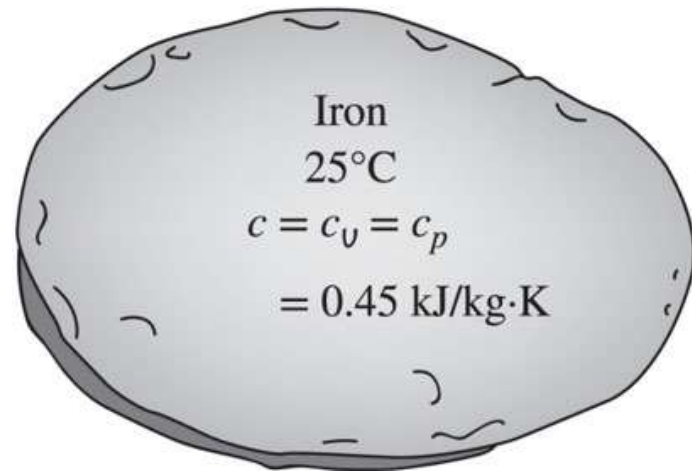


Figure 4–34

The c_v and c_p values of incompressible substances are identical and are denoted by c .

[Access the text alternative for slide images.](#)

4–5 Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids ₂

Internal Energy Changes

$$du = c_v dT = c(T) dT$$

$$\Delta u = u_2 - u_1 = \int_1^2 c(T) dT \quad (\text{kJ/kg})$$

$$\Delta u = c_{\text{avg}} (T_2 - T_1) \quad (\text{kJ/kg})$$

4–5 Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids ³

$$h = u + Pv$$

$$dh = du + v dP + P dv = du + v dP$$

$$\Delta h = \Delta u + v\Delta P \cong c_{avg}\Delta T + V\Delta P \quad (\text{kJ/kg})$$

For solids, the term $v\Delta P$ is insignificant, and thus $\Delta h \cong \Delta u \cong c_{avg}\Delta T$.

For liquids, two special cases are commonly encountered:

1. *Constant-pressure processes, as in heaters* ($\Delta P = 0$): $\Delta h \cong \Delta u \cong c_{avg}\Delta T$.
2. *Constant-temperature processes, as in pumps* ($\Delta T = 0$): $\Delta h = v\Delta P$

The enthalpy of a compressed liquid

$$h_{@p,t} \cong h_{f@T} + V_{f@T} (P - P_{sat@T})$$

Usually more accurate relation than $h_{@p,T} \cong h_{f@T}$

4–5 Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids ⁴

Cooling of an Iron Block by Water

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$0 = \Delta U$$

$$\Delta U_{\text{sys}} = \Delta U_{\text{iron}} + \Delta U_{\text{water}} = 0$$

$$\left[mc(T_2 - T_1) \right]_{\text{iron}} + \left[mc(T_2 - T_1) \right]_{\text{water}} = 0$$

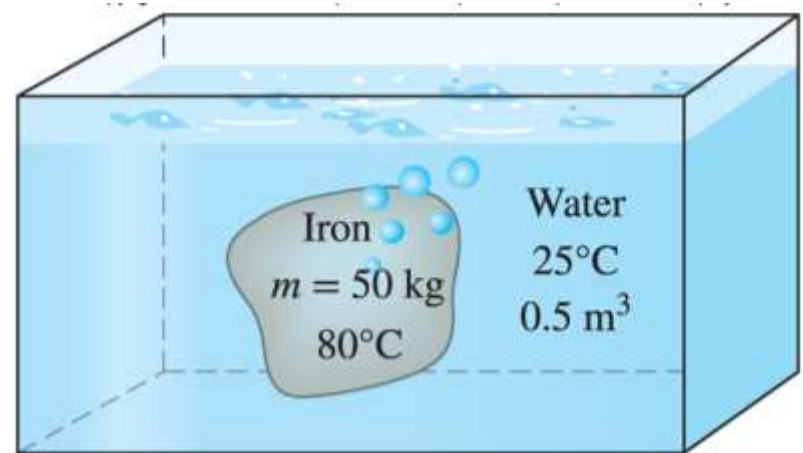


Figure 4–35
Schematic for Example 4–12.

[Access the text alternative for slide images.](#)

4–5 Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids ⁵

Cooling of Carbon Steel Balls in Air

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$-Q_{\text{out}} = \Delta U_{\text{ball}} = m(u_2 - u_1)$$

$$Q_{\text{out}} = mc(T_1 - T_2)$$

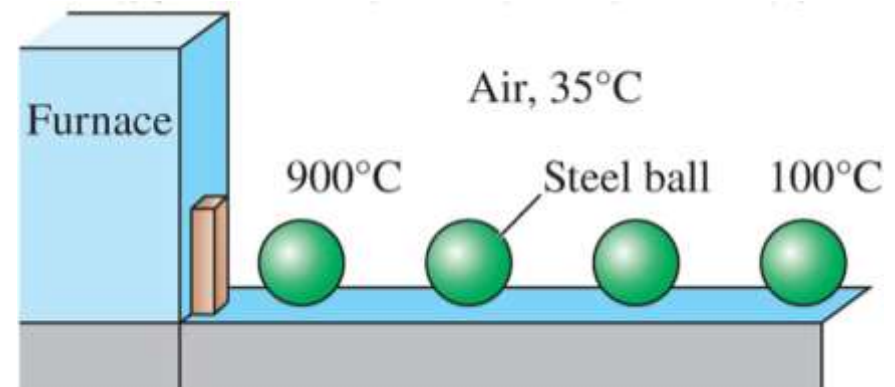


Figure 4–36

Schematic for Example 4–13.

[Access the text alternative for slide images.](#)

Summary

- Moving boundary work.
- Energy balance for closed systems.
- Specific heats.
- Internal energy, enthalpy, and specific heats of ideal gases.
- Internal energy, enthalpy, and specific heats of solids and liquids.